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A PRELIMINARY INVESTIGATION OF CATALYTIC COMBUSTION UNDER FLOW CONDITIONS

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A PRELIMINARY INVESTIGATION OF CATALYTIC COMBUSTION UNDER FLOW CONDITIONS

by

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Submitted to the Faculty of
Rensselaer Polytechnic Institute
in partial fulfillment of
the requirements for the degree of
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CATALYTIC COMBUSTION

I. Introduction

Catalytic combustion is a term used in this paper to describe heterogenous chemical reactions of surface contact catalysis where the desired objective is the liberation of heat. The reactions and process involved are such that the engineer would in general be unfamiliar with them. Consequently, prior to entering the discussion of catalytic combustion it is thought prudent to give historical background material and general information on catalytic reactions.

In general the material on catalytic reactions is of an empirical nature and no exhaustive cataloguing will be attempted in this paper. For more information on specific reactions a comprehensive reference list is furnished.

The subject of catalysis will be treated only in so far as it pertains to catalytic surface action. In speaking of catalysis only solid catalysts are included in this paper unless otherwise noted.

A. History

In general the investigation of catalytic combustion has been full of pitfalls for the investigator and misinformation for the student. Davy, the first investigator to

discover the phenomenon of catalytic combustion, in 1817[1*] in an experiment using a platinum sponge ignited a mixture of oxygen and hydrogen at room temperature. After this discovery Faraday, Henry, and many others attempted analysis of the problem but none were successful and interest died in 1836. Many erroneous conclusions were drawn from early experiments and it was not until the last part of the nineteenth century that more suitable explanations of catalytic combustion were acquired.

One of the principal experiments conducted by chemists at the end of the nineteenth century was the investigation of ignition temperatures and flame velocities by Victor Meyer and others. During the course of these investigations accuracy of measurement was largely thwarted by irregularities which could only be attributed to the influence of hot walls. The effect of those hot surfaces was found to be essentially a gaseous catalytic action and the work started by Fletcher[2*] on hot surface combustion has continued to this day.

The first accurate experimental measurements were made by M. Bodenstein in 1900.[3*] His experiments were carried out at both elevated temperatures in the incandescent region, and at room temperatures. The results of the experiments at elevated temperature were subject to many errors and were

[1*] W.A.Bone and T.A.Townend, "Flame and Combustion in Gases", pg.425, Longman, Green & Co., London, 1927

[2*] Bone and Townend, "Flame and Combustion in Gases", p.426

[3*] Ibid

inconclusive. The experiment at room temperature in which the rate of reaction of H_2 and O_2 over a platinum surface at temperature near 0°C was measured, led to important conclusions:[4*] that the catalytic action occurs as a result of surface adsorption of the reactants by the catalyst; that the reaction at the surface is instantaneous; and that the difference in measured rates is due to difference in diffusion factors. While these conclusions are not thought to be entirely valid nor all inclusive, they formed a basis for future thought at the time.

Since 1900 many experiments on catalytic combustion have been conducted but to this time no all inclusive theory as to the exact nature of the reaction has been reached. Bone, in England, has conducted research over a period of more than twenty-five years on catalytic combustion. His conclusions as to its nature are given in his book published in 1927: "The phenomena of catalytic combustion is probably dependent upon an adsorption or occlusion of the reacting gases by the surface where-by they become activated by association with it, and that in some cases such activation may be considered as an ionization of both the oxygen and the combustible gas".[5*]

[4*] M.C.Bodenstien, Zeit. Physik. Chem. 47, 1904, pg.52. Original translation, Bone and Townend, "Flame and Combustion in Gases", pp 432-433.

[5*] Bone and Townend, "Flame and Combustion in Gases", pg. 460.

Langmuir in a paper given before the Faraday Society in 1921[6*] indicated the same idea as given above except that he included the idea of valence forces between the reactants and the catalyst as being responsible for many characteristics. Although Langmuir was not primarily concerned with catalysis he conducted exhaustive experiments on gaseous adsorption in metals while developing the incandescent light. His paper, "Constitution and Fundamental Properties of Liquids and Solids,[7*] contains an analytical approach to the catalytic surface action.

By 1927 it was well recognized that catalytic combustion and other forms of catalytic action were definitely connected with the crystal lattice of the catalyst, and the atomic characteristics of the reactants in relation to the catalyst and to themselves. Since catalytic combustion is theoretically about the most complicated form of catalytic actions the reactions chosen for study to determine the cause of catalytic action were not of the combustion type. The experiments which were carried on in catalytic combustion were generally connected with explosion limit tests and high temperature wire ignition. An example is the work of R. S. Silver[8*] in determining the effect on ignition limits, when

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[6*] I. Langmuir, Trans. Faraday, Soc. 1922, pp 545-676
[7*] I. Langmuir, Journal of American Chem. Soc.38, 2221, 1916.
[8*] R. S. Silver, Phila. Mag. 7, (23), 633, 1937.

5 mm balls of different material at elevated temperature were fired into a gaseous mixture. The results bore out the conclusion of H. F. Coward and P. G. Guest,[9*] that catalytic materials of the same size and shape as non-catalytic substances required a higher temperature to ignite a given mixture. This phenomenon will be explained in later paragraphs.

At the present time there is very little investigation being done on catalytic combustion directly, but catalysis in gas-to-gas and gas to solid reactions plays a part in most reactions where heat is the desired product. There is some work being done on producing complete combustion by inserting surfaces in the combustion zone and also on hot wire ignition at high velocity flows. Most of this work is being done under government contract.

B. Contact Catalysis

Before discussing catalytic combustion specifically it is well to briefly discuss the theories on the cause of contact catalysis. However, it should be realized that the study of the cause of catalytic action is still in its infancy and only considered opinions and postulates, not a definite clearly defined analysis, can be given.

[9*] H. F. Coward and P. G. Guest, Journal Amer. Chem. Soc., Vol. 49, 2479 (1927).

In most chemical reactions the velocity at which the reaction proceeds is proportional to $e^{-\frac{E}{kT}}$, where E is the energy of activation and k is dependent on the type of reaction and the temperature.[10*] Since the catalytic action increases the rate of reaction at given temperature and constant k, there must be a decrease in the energy of activation if the rate function $e^{-\frac{E}{kT}}$ is still valid. In essence, the activation energy is used in stretching the bonds whereby the "radicals" of a reacting molecule are brought into a position facilitating the reaction with other atoms or groups of atoms.[11*]

Most present day theories agree that the decrease in energy of activation is a result of adsorption of the reactant by the catalyst, but there is little agreement as to the exact process by which it is accomplished. There had been a good deal of controversy as to whether the catalyst reaction occurred at the surface or in the body of the catalyst, but recent data on adsorption and reaction rates indicate that in most cases the reaction occurs at the surface. While adsorption of the reactants by the solid surface is a requisite for catalytic action, the converse statement is not true. The relation of adsorption of CO and catalytic activity of various catalysts illustrates the relation of adsorption to activity.

[10*] S. Glasstone "theory of Rate Reactions" McGraw Hill, 1941, pg58

[11*] J.E.Nyrop, "Catalytic Action of Surfaces", Levin and Munksgaard, Copenhagen, 1937, pp 36-40.

Order of catalysts activity *12

Adsorption of CO. (same time & temp.)	Co_2O_3	hopcalite	S_1C_2	MnO_2	CuO	Fe_2O_3	V_5O_5
Catalytic Adtivity	Co_2O_3	hopcalite	S_1C_2	MnO_2	CuO	Fe_2O_3	V_5O_5

H. B. Weiser[13*] indicates the two strongest explanations as to the decrease in energy of activation on adsorption as oriented adsorption and multiple adsorption. Activation by oriented adsorption consists in an alteration of the configuration of the adsorbed molecule, or the opening up of primary valence bonds or secondary or residual valence bonds as a result of the primary valence forces on the surface of the catalyst. Multiple adsorption is the independent adsorption of two ends of a molecule by active points on the catalytic surface. When these points are further apart than the normal length of the molecule, sufficiently strong adsorption will cause stretching and distortion which increase molecular activity. While these two theories can be applied in most instances, there are some catalytic processes in which the formation of intermediate compounds is found, i.e. decomposition of H_2O_2 on Hg., and these compounds could explain the catalytic action. Sabatier[14*] believes that the formation of intermediate compounds is the explanation for most catalysis but there is little experimental data to back his conclusion.

12* H.B.Weiser, "Colloid Chem.", McGraw Hill, 1949, pg.384
13* H.B.Weiser, "colloid Chem," 1949, Chap.7 on Contact Catalysis.
14* Ind. Eng. Chem. 18, 1105, 1926.

In comparing adsorption data as a measure of catalytic activity, the time for which the reactants will be in contact with the catalyst is important. Especially in the case of catalytic combustion where high flow rates are desired, the adsorption in .1 or .01 seconds is the important relation and there is no information on this.

While adsorption is the major criteria of catalytic action, the partial pressures of the reactants and the temperature of the surface are important in determining the end product. In combustion of hydrocarbons complete combustion is desired; so that an excess of stoichemetric air is desired and catalysts will be chosen for use which give end products as H_2O and CO_2 or products active enough to be readily converted to H_2O and CO_2. An excellent example of temperature effect is seen in the synthesis of hydrocarbons by a catalyst of cobalt carbonate and thorium carbonate mixed with dialomite; when a mixture of CO with twice its volume of hydrogen is admitted to the catalyst at 195°C or above, methane and CO_2 are formed; at 150-195 synthesis of oils occurs. If the pressure on the above reaction is increased, the length of the chains in the hydrocarbon oils produced is increased.

C. Effect of Surface Form on Catalytic Activity.

At low temperatures the surface of a given sample of catalytic material varys widely in catalytic activity. At

higher temperatures in the order of 2000°R each place on a given surface will have more nearly the same activity.

Samples of any given catalyst will vary greatly in preparation. There is no general reasoning which may be applied to determine the method of treatment to obtain greater catalytic effect. There has been a great deal of work done in determining the process by which maximum activity may be had for any given catalyst and reactant.[15*] Typical of this data is the table given below for reduction temperature and catalytic activity of nickel catalysts.[16*]

Temperature °C	Relative Activity
250	1.0
350	1.18
500	1.25
650	.23
750	.0

In many commercial applications the method of preparation and structure of the catalyst are a closely guarded secret since often many thousands of dollars and much time has gone into the research. The Germans did a great deal of

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[15*] R. H. Griffith, "Contact Catalysis", Oxford University Press, London, 1946, pp 129-197.

[16*] R. H. Griffith, "Contact Catalysis", pg 10.

work on preparation of catalysts in their development of catalytic hydrogenation and synthesis for synthetic production of hydrocarbons. This material which in most cases was not published is now available.[17*]

The effect of surface area on catalytic activity has not been successfully determined, probably because the methods of determining surface area were not indicative of the catalytic contact area. In experiments by Z.Schwab[18*] on catalytic activity of oxides of W, Zn, Ng and metallic nickel, an increase of catalytic activity did not correspond to a greater surface area per unit weight when the surface was determined by the adsorption of methylene blue. Other experiments have shown that a relation of surface area and activity does exist but no definite relation has been established. However, it is well known that a finely divided metal is more active than one in the massive state. In the above discussion the effect of heat release and temperature effects were not included. With catalytic combustion, where the catalyst and reactant are at approximately room temperature initially, the ratio of area to volume is extremely important. Since the velocity constant k is the form

$$k = a\,e^{-\frac{E}{RT}},$$

the rate of reaction increases as temperature increases. With

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[17*] Captured Technical Documents, "Catalysis".
[18*] Phys. Chem. 1931, 12B, 428.

a large area to volume ratio the temperature increases more rapidly than with a small ratio so the catalyst is brought to a higher temperature more rapidly and can be maintained at a higher temperature. Also there is a minimum particle size below which the maximum temperature will stay essentially constant for any size. The reason for this minimum size and its theoretical determination are still under study but no adequate explanation has been advanced.

It is well to point out here that most data on catalytic surfaces is compiled at temperatures below 1000°F which makes it difficult to determine characteristics when operating in flames. The data cannot be interpolated for high temperatures from low temperature curves. Not only does the effect of the surface change as the temperature is raised, but for any given reactant there is often a temperature at which a reversal takes place, and the reaction will not proceed, or slows appreciably when the temperature is raised beyond the reversal point.

Poisons

The explanation of a reversal in reaction rate is generally a result of poisoning. There are two general types of poisoning: one in which the poisoning comes from the presence of impurities in the catalyst; and the other in which the action comes from the reactants. The poisoning action

can be either permanent or transitory.[19*] The action is still the subject of much controversy, but in general the poisoning action comes from a film formation on the surface which prevents or retards the absorption of the reactants. The film may be of such a nature that merely changing the conditions or the reactants may dissipate it and allow the normal absorption to continue. An example of this type of poisoning is the action of CO and O_2 on a platinum filament. At 600°K the velocity of reaction is limited by a film of CO which prevents the adsorption of O_2, but at 900°K the CO film is broken and the reaction proceeds as fast as fresh material can be supplied to the surface. An example of permanent poisoning of a catalyst is the poisoning of platinum for the H_2 and O_2 combustion reaction by Cu; when the catalyst was heated to 1000° in a hydrogen atmosphere the cuprous oxide, which had been held immobile in the body of the metal was reduced and copper migrated to the surface of the catalyst where it formed a film and seriously retarded the catalytic activity.

Promoters and Carriers[20*]

Promoters are materials added to the catalyst in proper form which increases the activity of the catalyst.

[19*] Langmuir, J. Am. Chem. Soc. 38, 2221, 1916, Griffith, "Contact Catalysis", Chapter IV.
[20*] R.H. Griffith, "Contact Catalysis", Chapter III.

The additions are generally small. If the promoter is catalytically active, the activity of the mixture will rise to a sharp peak at some percent of addition and then will decrease to a constant value slightly greater than the pure catalyst as the percent of promoter is increased. There is no comprehensive explanation of promoter action. In some instances the distortion of the crystal lattice found from X-ray photographs coincides with the increase in activity, but the exact nature of the action is as obscure as in the exact nature of catalysis.

Carriers are catalytically inert materials which are used as a holder for the catalyst and are of great importance commercially. The carrier does not add to the activity of the catalyst. Often it permits the catalyst to be distributed in a more effective form with the result that the same activity may be had with only a small percent of the weight in the pure state. In catalytic combusion the use of carriers is important , for it permits the use of refractories as holders of the catalyst and greatly increases the temperature range of use. Also the active catalysts are generally very expensive and the use of carriers gives the same effectiveness at a much lower cost.

D. Catalytic combustion and analysis of the problem.

The problem presented in this paper is to consider the applications of catalytic combustion in engineering with special emphasis on its uses in flow combustion. Two general ideas will be considered: catalytic ignition and catalytic combustion in a low temperature gas stream.

The subject of hot point ignition has been studied for a considerable period and the characteristics for most fuels are well established under static conditions.[21*] In general, the smaller the body the higher its temperature must be to cause ignition, and the greater the ratio of gas to air the higher the ignition temperature. A typical example of the size and mixture effect is the data from the work of Coward and Guest[21*] shown on Curve 1, for methane and air at atmospheric pressure in a large volume. The lowest measured ignition temperature for methane is 645°C which is found with extreme turbulence on a hot wall.

The same work by Coward and Guest[21*] determined the effect of various materials on ignition temperature. These results shown on Curve 2[21*] are typical of the effect of catalytic material on ignition temperature. The fact that

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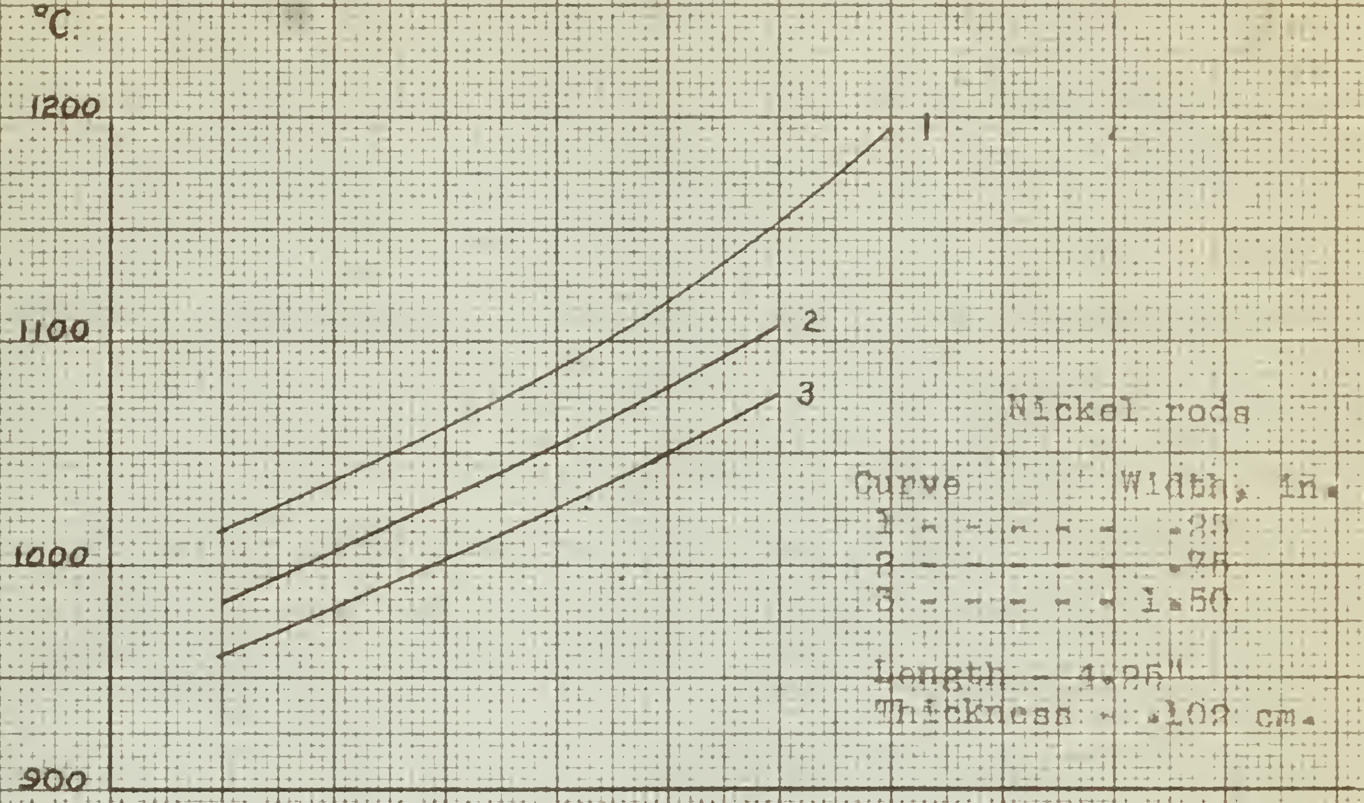
[21*] W. Jost "Explosion and Combustion Processes in Gases", McGraw Hill, 1946, pg 21-32.
Coward and Guest, J. Am. Chem. Soc. 49, 2479, 1927.

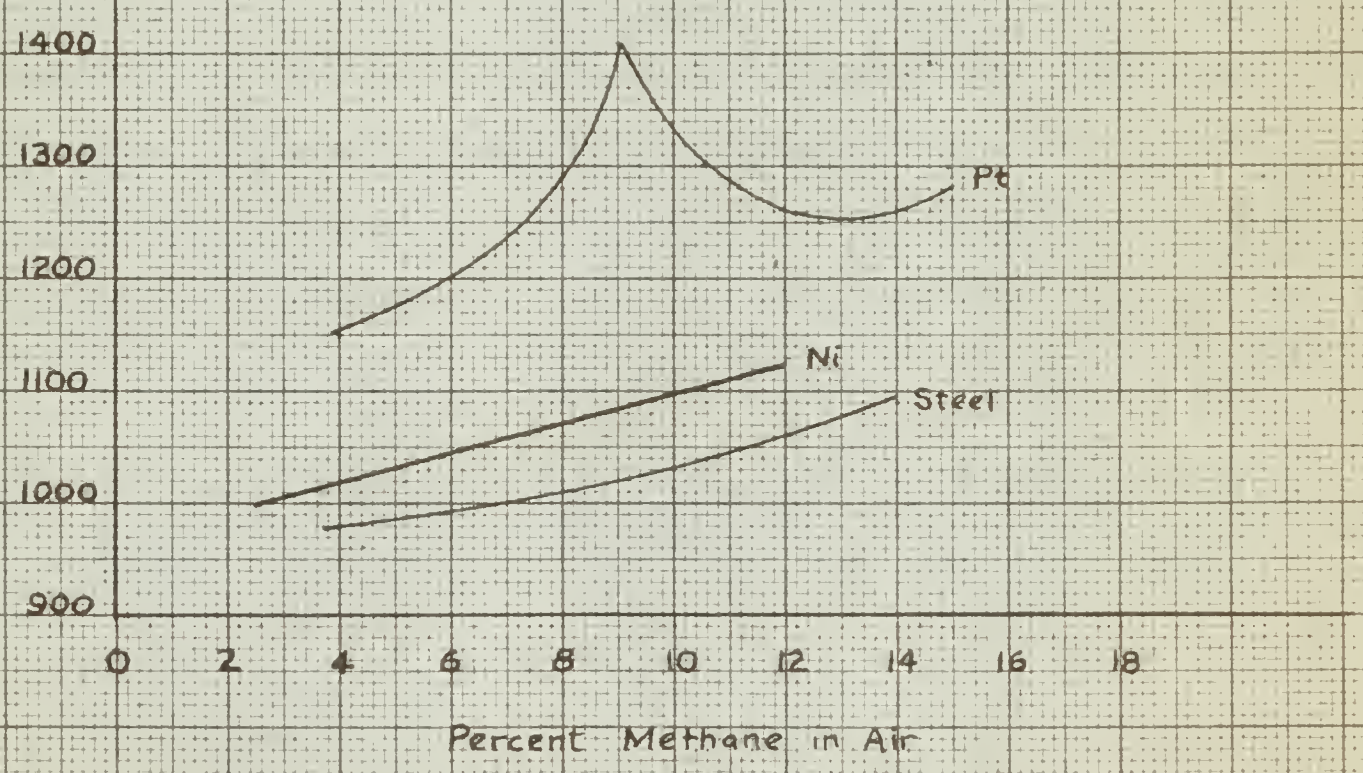
CURVE 1

Ignition of Methane in Air



Ignition of Methane in Air

CURVE 2



platinum, which is the most active catalytically, also has the highest ignition temperature is explained by Coward and Guest. "In the immediate proximity of the platinum surface, there is a very active reaction. Since the reaction is not confined strictly to the surface, there is, in the immediate proximity, a rise in the temperature in the gas with a relatively steep maximum, with a sharp bend in the temperature curve and thus a great loss of heat at the maximum, especially toward the side of the greater drop in temperature, the metal surface. The conduction of heat can, therefore, balance out the production of heat by chemical reaction and hence no ignition takes place."[21*] In the opinion of this writer, the results can be more satisfactorily explained by the fact that in catalytic reactions the reaction is entirely on the surface of the catalyst. Since in the surface reaction no chain carriers are produced, the activated particles necessary for ignition in the mass of the gas must come from those molecules which strike the surface and do not react but pass through a film of combustion products and re-enter the unreacted gas to react. The number of activated particles entering the unreacted gas will therefore be less with a catalytic surface than with the non-catalytic surface at the

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21* W. Jost "Explosion and Combustion Processes in Gases", McGraw Hill, 1946, pp 21-32
Coward and Guest, J. Am. Chem. Soc. 49, 2479, 1927.

same temperature, and a higher temperature for ignition will be required of the catalyst.

In the experiments discussed above, the heat for the igniting body was supplied from an outside source. There are known combinations of catalyst and reactant which have an appreciable reaction velocity at room temperature and liberate heat upon reaction. Continuous ignition in a stream of air fuel mixture could be accomplished, without use of external energy, by insertion of catalytic material in such a form that its temperature was maintained by catalytic combustion at that required for ignition. As was indicated in the section on catalytic surfaces, the form of the catalyst is extremely important. The first phase of the experiment was chosen to be the determination of a catalyst, fuel combination, and the form of the catalyst required to produce a catalyst temperature high enough for ignition of the fuel . After determining the catalyst, its form, and the fuel, the effect of stream velocity on the unit would be investigated. The primary purpose of this phase was not to develop an igniter but rather to determine a catalytic system which could be used in determining general characteristics of catalytic combustion in a flowing stream.

The second phase of the experiment was to install the system decided on in the first phase and test the charac-

teristics of catalytic combustion for various fuel air ratios and stream velocities. Since it is desired here to test the catalytic combustion characteristics, a flame is not desired and operation of the experiment must be such as to prevent the formation of a flame. No attempt will be made to determine the reaction products which indicate the degree to which the fuel has been oxidized. The ordinary Orsatz analysis would not give the desired information and an involved chemical analysis is needed because there is a wide variety of oxidation products possible in catalytic oxidation. With the oxidation of methyl alcohol on platinum, aldehydes, ketons, carbon dioxide, and water are probable products. Since the production of heat and not the production of chemical products is the objective here, the measurement of temperature as a criteria of heat release is the important factor.

The action of incandescent surfaces in combustion is important in a catalytic combustion reaction where there is flame as well as catalytic combustion. In catalytic combustion the temperature of the catalyst will generally be in the incandescent region and so the surface will act as an incandescent surface. The primary distinction between incandescent and catalytic surface combustion is that in the former the reaction occurs at a finite distance from the

surface, while in the latter, reaction occurs in the surface of the material. An incandescent surface will activate unreacted fuel or oxygen particles which strike it and when those particles contact an unlike fuel or oxygen molecule a reaction occurs. Also if particles of fuel and oxygen strike the surface at the same point a reaction occurs.

At present there are few uses of catalytic combustion but as the demand for higher rates of burning with smaller areas is increasing it is believed that the use of catalytic combusion may provide an answer to some of the problems. The work presented here is intended as a first step in the application of catalytic combustion to present day combustion problems.

II. The Experiment.

A. Materials

The first phase of the experiment was to determine the system of fuel and catalyst to be used. Since the fuel air mixture was to be supplied at room temperature and the catalyst was initially to be at room temperature, the combination of fuel and catalyst would have to have an appreciable reaction velocity at room temperature in order to increase the temperature of the catalyst.

Since it was not possible to test a great variety of catalyst fuel systems the selection was principally an analytical one. The most active catalytic combustion system with common substances is the system of oxygen-hydrogen and platinum asbestos, platinum sponge, or very thin platinum wire. However, this system has the disadvantage of producing high heat release and is extremely difficult to control.[23*] In hydrocarbon oxidation platinum is the most active catalyst, approximately twenty times greater than nickel under the same conditions,[23*] therefore it was determined to use platinum as the catalyst in these tests. The American Platinum Works of Newark, New Jersey, produces platinum

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[23*] W. Jost "Explosion and Combustion Process in Gases", pp.26028. H. F. Coward and P. G. Guest, Jour. Amer. Chem. Soc. Vol. 49, p.2479, 1927.

and palladium in all forms for use as catalysts, and they recommend platinum for use in oxidation catalysis.[24*] The form of the platinum for best results could not be determined from analysis but it must have a large surface area and a high surface to volume ratio, as has been discussed in the Introduction.[25*] The forms chosen for test were: .003" platinum wire, 10% rhodium platinum screen .003", 80 mesh and .5% by weight platinum asbestos. Platinum black was not considered here because of the difficulty of bonding the material to permit its use in a flowing stream; however, platinum in this form is extremely active and would provide an excellent catalyst if a suitable holder could be found.

For fuels the alcohols provide a cheap, readily available material which can be used as a liquid or gas since they have a low boiling point. With most catalysts isopropyl and methanol have the greatest activity, of the alcoholes.[26*] Since methy alcohol is more readily available it was chosen. In addition to methanol it was decided to use propane as a fule. Propane was chosen because it is safer to work with than most other gaseous fuels and also because it represents a class or fuels which are not as susceptible to catalytic action as is methanol.[26a*]

[24*] American Platinum Workds-Bulletin "Platinum & Palladium Catalysts", Newark, N.J.

[25*] B.H.Griffith, "Contact Catalysis" pp.25-26

[26*] B.H.Griffith, "Contact Catalysis" pg 230

[26a*] W. Jost "Explosion and Combustion Processes in Gases" McGraw Hill, 1946 pp.436,379

B. Apparatus

In all of the investigations undertaken in this experiment it is necessary to have a metered air supply, a fuel injection system, and a means of controlling each independently. The apparatus must be as flexible as possible to permit tests of a various sizes and composition of catalysts.

Photograph I shows the assembled apparatus and a description of each component is given below .

Air Source

Air was supplied by a centrifugal blower rated at 175 cu. ft./min. at 3475 rpm. This source was chosen rather than the compressed air system supplied by a reciprocating compressor to avoid possible contamination of the catalyst by impurities found in that system. In order to maintain constant supply pressure from the blower a large valve was installed two feet from the blower. It could bleed air from the system when flows were low and could be closed at high flows; in this way a constant supply pressure of any value from 16 to 24 inches H_2O gage could be maintained. A 3" pipe was used to conduct the air from the blower to the metering orifice.

Air Metering

The air was metered by use of a flat edge orifice designed and installed according to the standard specifications of the American Society for Mechanical Engineering: Fluid Meters, Parts I, II, III, N.Y. Soc. 1931 and L. S. Marks "Mechanical Engineers Handbook," pages 2098-2099. The theory and investigation of these meters is fully covered in the above named publications. Under the conditions of this installation an error of less than 3 percent in measurement of volume flow is indicated. The orifice was 1.531 inches in diameter with pressure taps one-half inch upstream and downstream. The differential pressure across the meter was applied to an inclined water manometer which could be read with an accuracy of plus or minus two thousandths of an inch of water.

Fuel Supply

Propane gas C_3H_8 is manufactured and sold commercially as "Pyrofax". The gas is liquified and used in containers that hold approximately 90 pounds of Propane and have a pressure of approximately 135/lbs.sq.in. absolute at room temperature. The characteristics of "Pyrofax" from data of the Union Chemical and Carbide Company are given on the following page.

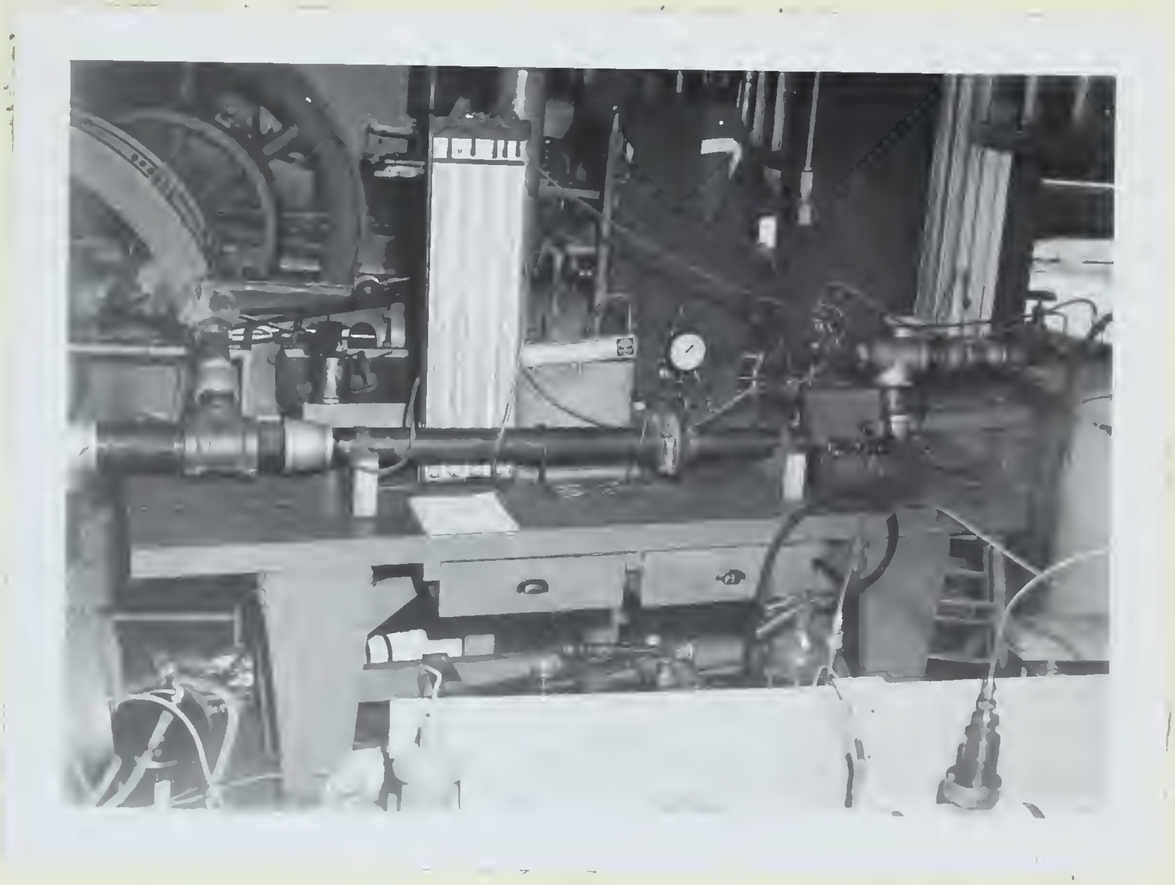


PHOTO
1

Heating valve	21,500 Btu/lb.
Boiling point	-45°F
Critical pressure	66 lb/sq.in.
Ratio of specific heats	1.153
Vapor pressure 22°C	117 lb/sq.in.gage
Specific gravity (Air=1)	1.56
Stoichiometric combustion ratio	$\frac{24 \text{ cu.ft.air}}{\text{cu.ft.fuel}}$ $\frac{15.8 \text{ lbs air}}{\text{lbs. fuel}}$

At low flow rates the pressure in the tank will remain constant; but at fuel rates of .005 lbs/sec. or greater, the cooling effect from evaporation will cause a drop in pressure of as much as 20 lb/sq.in. With runs of less than three minutes the effect will not be appreciable and the tank pressure will remain essentially constant even at higher flow rates. The propane was metered using the same system as was used in previous experiments on flame holders.[27*] A gage of the type used on welding units is attached to the propane tank, this is connected by a rubber tube to a control valve which admits the fuel to the injector in the air stream. The control valve has a pointer attached which makes it possible to open it to the same point for all runs. The pressure on the line is controlled by a screw on the tank gage. The system is calibrated by determining the time required for a

[27*] J.P.Field "Theory of the Flame Holder", Masters Thesis submitted at R.P.I., June 1947, pp.12-14.

pound of gas to flow at various gas pressures. The propane tank is mounted on a weighing scale which can be seen in Photograph 1. The calibration, found to be a nearly linear relation of pressure and fuel rate, is plotted on Curve 3.

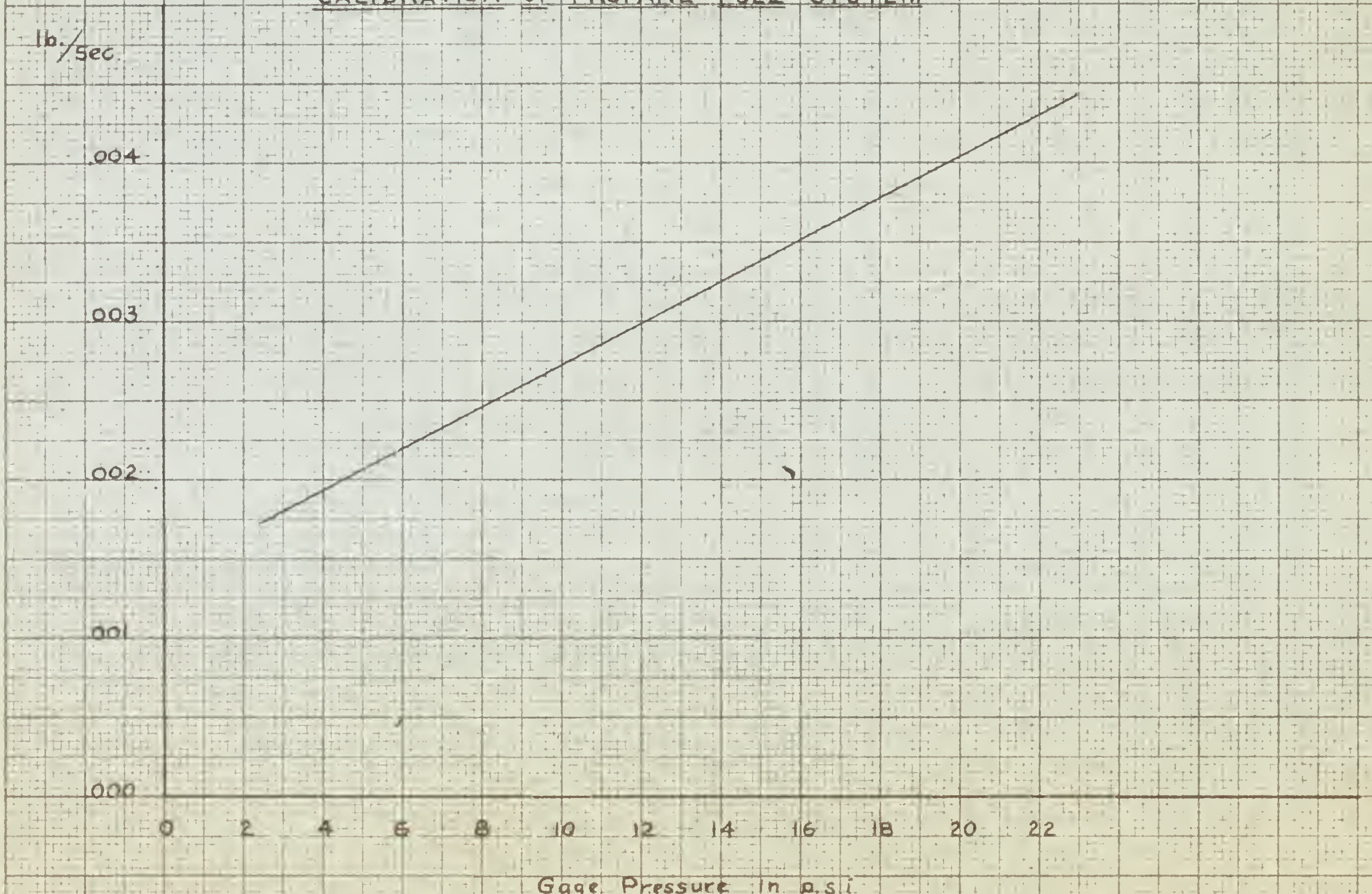
Methyl alcohol CH_4O has a boiling point of 149 degrees F., a specific gravity of .791 at 60 degrees F., a stoichiometric air fuel ratio of 6.46, and an ignition temperature of approximately 950 degrees F. under static conditions.[28*] The exact reason for the catalytic activity of methanol with platinum is not known, but it is believed to be a result of the type of bond in the molecule of the fuel. One method of alcohol production is the catalytic oxidation of methane on platinum. The combustion of methyl alcohol on a catalyst does not give definite combustion products but, like most catalytic reactions, will produce a variety of products whose composition depends on the temperature of the catalyst and the air fuel ratio.

The methanol will be metered by weighing the amount used at definite settings for a given time. Two methods of injecting the alcohol into the air stream will be used. The first will supply liquid alcohol under low pressure to a jacketed tube (.265 inches inside diameter) mounted in the air stream; inside the tube are 7 number 80 holes which are drilled on a circle and the fuel from all holes will

28* O.W.Eshback, "Handbook of Eng. Fundamentals" 1-111
Jost. "Exp. and Com. Processes in Gases", pg.45.

CURVE 3

CALIBRATION of PROPANE FUEL SYSTEM



meet in the center of the tube. The fuel is controlled by varying the head on the system either by elevating the fuel container or supplying the desired pressure from the air system. The second method used is to pump air through the fuel reservoir to vaporize the alcohol, and then pass the mixture through a rubber hose to a tube mounted concentrically in the air stream. The quantity of fuel vaporized is measured by weighing, and the control is accomplished by varying the pressure on the air supply which varies the air flow through the fuel. The air is supplied by a takeoff from the main 3 inch air pipe. The vaporization can also be increased by putting cotton on a wire rack in the alcohol container so that the evaporation area is increased. Since one of the objectives here was to have the fuel at room temperature, the system of heating the alcohol in order to vaporize it was not used, but it would be a more flexible system in future work. The maximum flow with the system used was .6 lb/hr and flow control was poor.

Control Valve

The control valve for the main supply flow was a one-and-one-half inch gate valve installed three feet downstream from the metering orifice and immediately upstream from the test section. The valve gave exceedingly sensitive control of the flow.

Test Section

Two test sections were used. Test section I consisted of a one foot length of one inch steel pipe with: a pressure tap two inches from the upstream end; a fitting for admission of methanol in either vapor or liquid form to a tube, (which was held concentrically in the pipe by the fitting) that could be placed in a position either two inches or four inches from the downstream end of the pipe; and a flanged joint on the end with a fitting for attaching two thermocouples on the downstream half of the flange. Stainless steel screen could be placed between the sections of the flanged joint in order to hold the various catalysts in the stream. The size of screen used was determined by the form of the catalyst used, for most tests a .0128 inch wire , 40 gage screen was used.

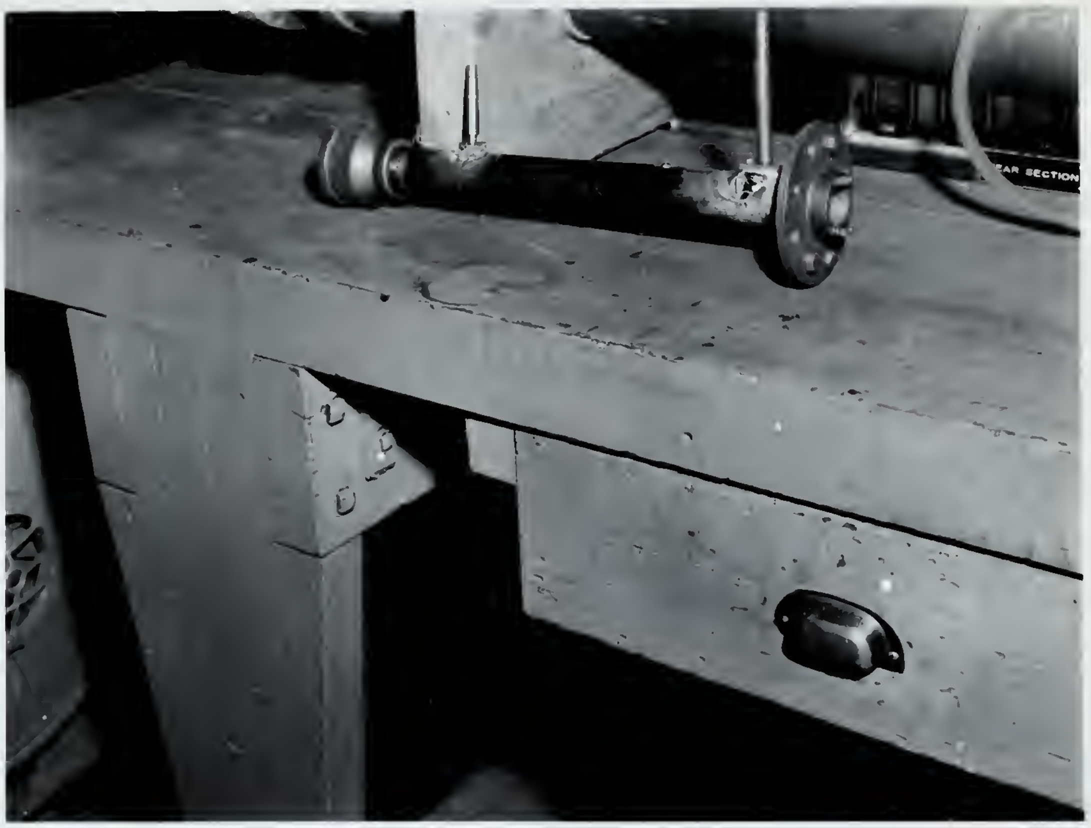
The second test section was similar to the first except that it was an eight inch piece of one-and-one-half inch pipe and the concentric tube had a small fitting on the downstream end to which the stainless steel mesh with catalyst could be attached. The downstream end of the pipe was not flanged but was threaded so that additional pipe could be connected if desired. A fitting for insertion of a thermocouple was provided one-half inch downstream from the point of attachment of the mesh. The test sections

were attached to the control valve as is shown in photograph 3. Photograph 2 is of the first test section and photograph 3 of the second.

Pressure and Temperature Measurements

Pressures were measured with water manometers graduated to one tenth of inch for pressure on the orifice, pressure on methanol supply, and pressure in the test section. For the differential pressure across the orifice a one inch inclined water manometer, graduated in hundredths of an inch was used.

Temperatures were measured at the center of the pipe. A chromel-alumel thermocouple was used in which the wire was enclosed in a silicate surrounded by a metal casing. The temperature readings of the catalyst were obtained by forcing the thermocouple on the metal or inbedding it in the asbestos. The readings would not be the exact temperature due to radiation andother corrections, but the variation of temperature during any given test with change of conditions was the desired result. The results desired were not dependent on accurate determination of any temperature, but rather the variation of temperature with test conditions was the important factor and this was achieved.



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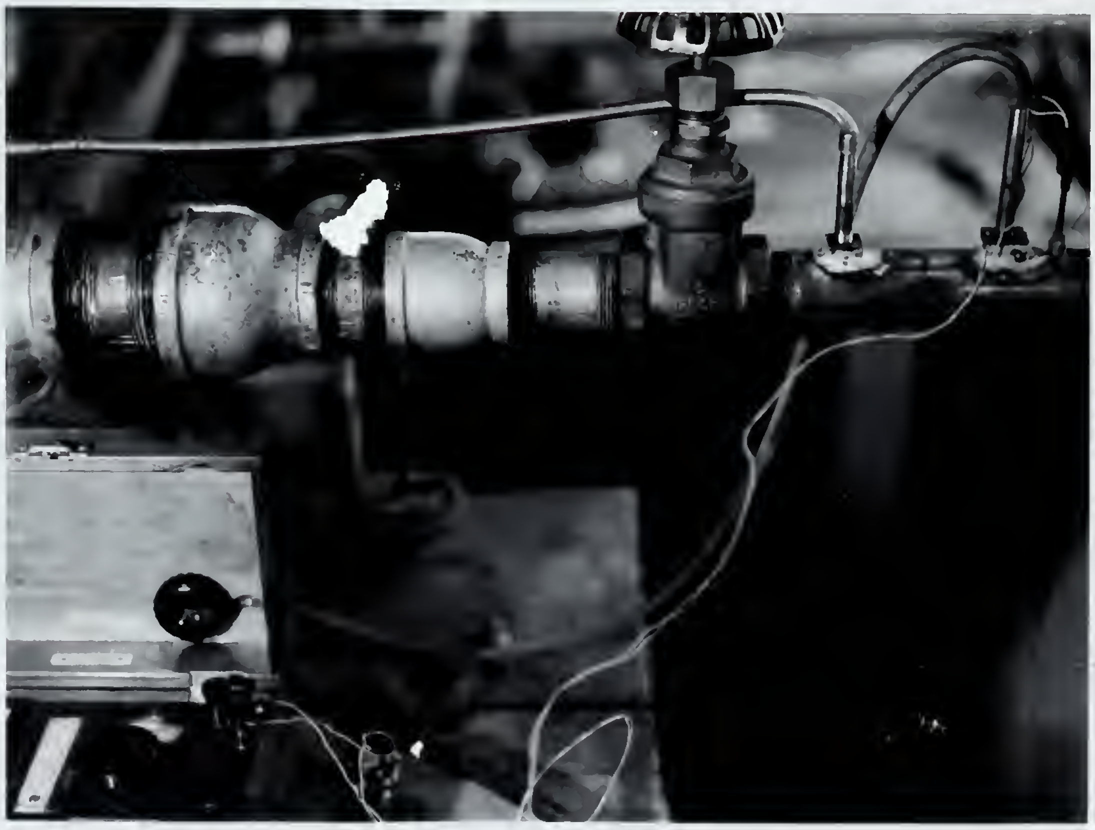

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3.

C. Procedure and Results

The procedure and results of each test will be discussed jointly, since the procedure and purpose varies with each phase.

Liquid Methanol platinum in the three forms; a wire, asbestos, and screen, previously described, were tested using liquid methanol. The methanol was injected in the air stream in the one inch test section as a fine spray about four inches upstream from the screen containing the catalysts but no appreciable reaction could be produced. With the platinized asbestos, occasional points of incandescence would appear but would extinguish immediately and no temperature increase was observed on the thermocouples. One of the thermocouples was in contact with the asbestos and stainless steel screen and the other was in the center of the one half inch downstream from the screen. Various fuel rates and air flows were tried. The point of injection was moved two feet upstream but there was still no measurable reaction. It was noted, however, that as the rate of flow was increased the number of incandescent points appearing increased. With the platinum wire and screen no effect at all was noted. A system, suggested by the catalytic cigarette lighter, of surrounding the platinum wire with a metallic oxide and placing this between the stainless steel screen holder gave much

the same result as the platinum asbestos with occasional points of incandescence. When fuel had been flowing for more than half a minute no further incandescent points could be noted. The fuel had to be shut off and the catalyst dried by running from three to five minutes at maximum flow before another test could be made. No test data was compiled on this phase as there was none of interest noted. For the test with the asbestos and the wire material they were enclosed in the stainless steel, 40 gage and .01 inch wire, screen so that there was considerable resistance to flow, the maximum flow being .1 cu.ft/sec.

Methanol Vapor Test

This test was run by setting a definite fuel rate and varying the flow rate of air. Since air was used to carry the vapor from the alcohol reservoir to the test section the fuel was already mixed. It was injected through the tube mounted in the center of the pipe, the end of which was about one inch from the catalyst. The entire flow had to pass through the screen. The tube was threaded on the upstream end so that a plug could be inserted to prevent passage of air from the main stream and produce a higher concentration of alcohol at the center of the catalyst.

Platinum Asbestos

One half gram of asbestos was placed between the two pieces of stainless steel 40 gage screen. When the flow was first passed through the asbestos no increase in temperature was noted. The flow rate of alcohol was varied but no reaction occurred. It was found that if the alcohol air mixture were passed through at very low velocity in the order of one foot/sec, the reaction would start as indicated by temperature increase, and then the flow velocity could be increased without stopping the reaction. The resistance of the asbestos in the screen was such that the flow rates were too low to measure if all of the flow were passed through it. However, it was found in these tests that the temperature versus fuel rate at a constant air flow showed a rapid rise up to a value of one ounce per hour and then the temperature stayed essentially constant as the flow rate was increased. Varying the air flow changed the maximum temperature but did not change the character of the curve or the fuel flow at which the curve leveled off. The maximum temperature found here was 400 degrees F. Since the air flow was of too low a magnitude to give a drop in pressure on the orifice, two slots were put in the side of screen to permit passage of air fuel mixture. Under this system the flow went entirely through the slots and no temperature increase

was observed. One of the primary difficulties here was clogging of the screen by the asbestos after a short period of operation. Another difficulty was the inability to produce high flow rates of alcohol.

During these tests the reaction was not that of complete combustion and the products were not CO_2 and H_2O. Their presence was detected by the extremely pungent odor of the exhaust products which greatly irritated the eyes and nose. This material is probably formaldehyde or one of the other aldehydes.

The data from these tests are not included since the values for different runs were not reproducible. Only general qualitative information was obtained which has been included in the first paragraph of this section.

Platinum-Wire and Platinum Screen.

The tests using a .005 inch strand of platinum wire and a piece of .005 inch by .5 inch platinum foil in the stream showed no reaction for any fuel rate or flow. The .003 inch, 80 gage platinum screen did not show any reaction either. However, with the lighter system mentioned previously, under materials, using .003 inch platinum wire in a promoter of oxide, a rapid reaction occurs at room temperature. The reaction proceeds instantaneously as far as could be determined. The catalyst was held by the stainless steel screen, but only

a circle of .3 inch radius in the center was filled with the catalyst so that higher flows could be had. The flow from the alcohol tube covered about one tenth of the flow area and so gave a considerable enrichment at the catalyst. Using low air flows ignition occurred with the two alcohol flow rates tested. These tests were made without a plug in the alcohol injection tube. Typical results from these tests are shown on Curve 4 and Appendix A-1. As ignition occurred there was an increase of approximately 800 degrees in catalyst temperature and 1100 degrees in air temperature. Prior to ignition the pungent odor mentioned previously was evident. In these runs the reproducibility was good, however, at high flow rates the promoter which is in fine particles was blown out and after five or six runs the catalyst was operating at fifty percent effectiveness and had to be replaced. The tests were also limited by the low maximum fuel rate, .6 lb/hr, and difficult control of the alcohol system, but they give good indication of general characteristics of temperature and velocity at constant fuel flow.

A combination of platinum asbestos and a 3 inch piece of .003 inch wire in it was tested. It was subject to the same difficulty as observed with asbestos alone but a consistent maximum temperature of 850°F degrees

could be obtained by adding the platinum wire.

Propane tests

Using propane alone in all fuel-to-air ratios there was no measured reaction with any of the catalysts.

Propane and Alcohol tests

With platinum asbestos and 3 inch platinum wire in the stainless steel screen, where all flow goes through the screen; if alcohol is first admitted and then a small flow of propane will cause a jump in temperature. With an alcohol fuel flow of .125 lbs. per hour the temperature of the screen is 310°F, when propane is admitted the temperature rises to 850°F and will remain approximately constant if the alcohol flow is stopped. In this test, as mentioned before, the restriction of flow made it impossible to get more than general qualitative information. As the flow of propane was increased the temperature remained essentially 800 degrees F until a rate of .004 lbs/sec of propane was reached. At this flow the temperature started decreasing and with a slight increase in flow rate the reaction stopped completely. When the alcohol was allowed to flow again there was no reaction. The catalyst was heated to about 700 degrees and cooled in air. After this treatment the alcohol reacted as it had in the first run although the temperature was slightly lower 290 degrees F.

From the results just described it was decided to run a test using alcohol to start; then introducing propane and varying its flow with a constant air flow. In order to get measurable flow, openings were made on the sides of the stainless steel mesh holding the platinum asbestos and .003 inch wire. After each run a prick was used to clear the screen of the asbestos which eliminated much of the trouble previously encountered. The runs were of short duration to prevent clogging of the screen and also to keep temperature drop and consequent pressure drop, due to evaporation of propane, to a minimum. Typical results from the tests are shown on Curve 5 and Appendix A-2. Ignition of propane could not be accomplished. The pyrofax gas has a very destinctive odor and during the tests this was prominent. The pungent odor observed in previous tests was observed when alcohol was on but disappeared when the alcohol was shut off. The maximum flow obtainable here was .205 cu. ft. of air per second. As is shown from the data, the screen temperature and the air temperature followed almost exactly the same path with the screen temperature about twice the gas temperature in most cases. While the temperature measurements will be subject to inaccuracies mentioned under Temperature Measurement, for any run, the variation of measured temperature with fuel rate and flow will be the same as the vari-

ation in true temperature.

The platinized asbestos showed wide variation in activity with use. After more than one-half hour at temperatures above 500 degrees F, it was found that the activity, as measured by alcohol reaction at low flows, had decreased as much as fifty per cent. After each series of runs the asbestos was replaced, and it was found that new material gave very consistent results with alcohol at low flows in most instances. The quantity of asbestos used had no measurable effect on the temperature characteristic, but with more material the stainless screen clogged faster, and the effect of the quantity of catalyst was difficult to determine. No change in the platinum wire could be observed.

Flame Holder Tests.

Using test section 2, (Photograph 3) a one inch square of stainless steel screen holding platinum asbestos and a one inch section of .003 inch 80 mesh platinum screen inside was placed on the holder. The sides of the screen were bent to an angle of 60 degrees, .25 inches in from the edge. The purpose of the tests was to test the re-ignition properties of the unit. However, it was found that the propane would not produce self-ignition under any circumstances. The alcohol ignition occurred readily with low flow velocities but when the propane was admitted to the stream the

flame stopped. There was insufficient time to study this problem as it would require a rebuilding of the entire setup and considerable experimentation.

III. Interpretation of Results

The results of the first phase of the investigation show that it is possible to produce ignition of an alcohol air mixture with both catalyst and mixture initially at room temperature. Even more important is the effect of the form of the catalyst on its properties as shown by these tests. The difference in results of the tests of platinum asbestos, platinum wire, and platinum plus promoter where the average maximum temperature of the asbestos alone was about 800 degrees lower than that of the platinum plus promoter and the .003 inch wire by itself produced no reaction at all, show that with any given catalyst fuel system the form of the catalyst is the most important single factor.

The fact that liquid alcohol when sprayed into the system in fine particles failed to produce appreciable reaction is easily explained. The catalytic reaction occurs as a result of adsorption of fuel and air by the catalyst. The adsorption of air is prevented by a film of liquid fuel on the surface of the catalyst. This is shown clearly by the fact that an air stream had to be passed through the catalyst, after a run using liquid alcohol, for a considerable period to dry it out before it would provide reaction with the gaseous materials again.

The results of the tests with platinized asbestos show that there is a maximum reaction rate for the catalyst in a given form with a given fuel. This value cannot be determined analytically as has been mentioned before under catalytic surfaces, but the relation of particle size to reaction rate in a general way is shown by the inability of platinum foil .003 inches by .8 inch to cause any reaction while the .02 grams of platinum in the asbestos caused appreciable reaction.

From the combustion viewpoint, the fact that in all of the tests, where only catalytic oxidation occurred, the combustion was incomplete is very important. The fact was clearly shown by the observed presence of pungent gases in considerable quantity and also by the fact that when ignition occurred the temperature of the catalyst was raised almost 800 degrees and the temperature of the gases was raised about 1100 degrees. Whether the ignition raises the temperature of the catalyst or whether the combination of surface and catalytic combustion produces the increased themperature is difficult to tell.

The exact values of the temperatures determined are of not too great significance except as they correlate the data; but they do give an indication of the approximate temperature which the system of alcohol platinum will give. The ignition temperatures of methanol is about 1100 degrees

for the conditions as used in this experiment, the temperatures read at the point of combustion varied from 700 degrees to 1100 degrees. When combustion was prevented temperatures as high as 2000 degrees were observed on the platinum and promoter. There were probably isolated hot spots far in excess of the recorded temperature which could cause ignition. In these tests ignition could only be achieved at low flows, but it is believed that this is a limitation of the alcohol fuel system. From results obtained in the experiment it is indicated that a catalytic igniter would function at high velocities when sufficient fuel is used in the system. It is also apparent by comparing the results of the propane and alcohol tests that alcohol, or some other easily catalyzed fuel, would be necessary to maintain high temperatures on a catalyst for ignition.

In all of the forms in which the platinum was used, a large pressure drop at high velocity was required if all of the fuel air mixture was to pass over the catalyst and react. While no attempt was made to determine design characteristics of a catalytic combuster, it is easily seen that if the area of the unit is increased the velocity decreases and the head required to force a given amount of fuel mixture would decrease as the square of the velocity. Also the packing of the material has a great effect on the resistance to flow.

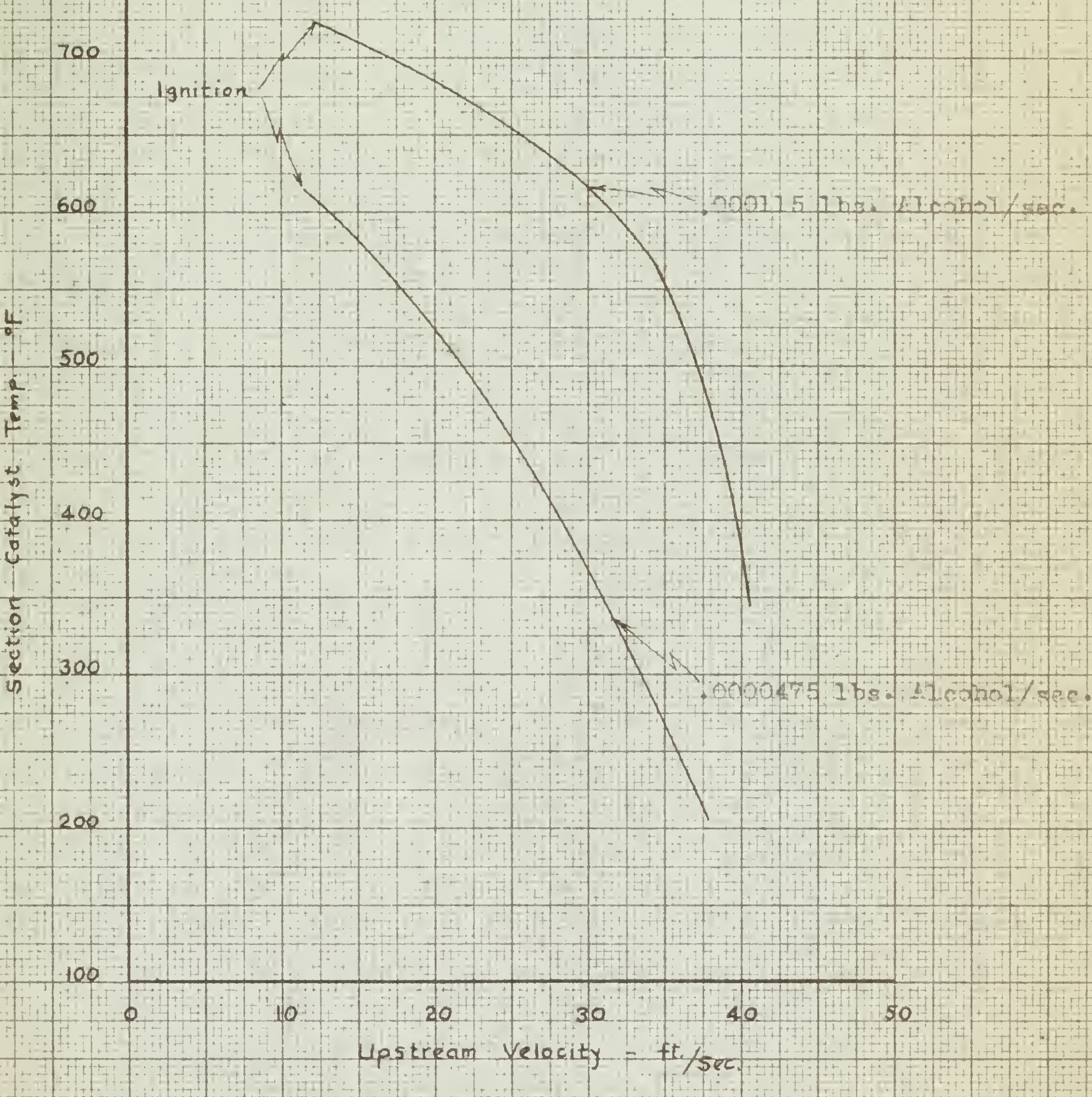
The difference in catalytic effect of two fuels is shown clearly from data presented in Appendix A-2. The alcohol at a flow rate of .000045 pounds/sec produces a temperature in the catalyst approximately the same as the propane at a rate of .0018 pounds/sec. The alcohol is essentially concentrated on an area of one-tenth the area covered by the alcohol; but even considering this the difference is great. The fact that propane will not react with the platinum catalysts at room temperature while the alcohol will, is a good indication of the fuel's behavior with the catalyst.

With propane, the air fuel ratio for maximum temperature is about 8:1, an increase of fuel above that produces a decrease in temperature until a ratio of about 5:1 is reached; and then the temperature drops rapidly indicating temporary poisoning of the catalyst. The values of air fuel given above are to a certain extent influenced by the form of the catalyst, but they would be in the same range no matter what the form of the platinum catalyst.

Curve 4 shows the essentially linear character of upstream velocity versus temperature. This is expected with the low flow of alcohol used since all alcohol reacts and the maximum adsorption rate is not reached. The slope of the curve is a function of the way in which the catalyst

CURVE 4

Test of Methyl Alcohol with .0706 sq. in. of Platinum wire and Promoter in Test Section 1



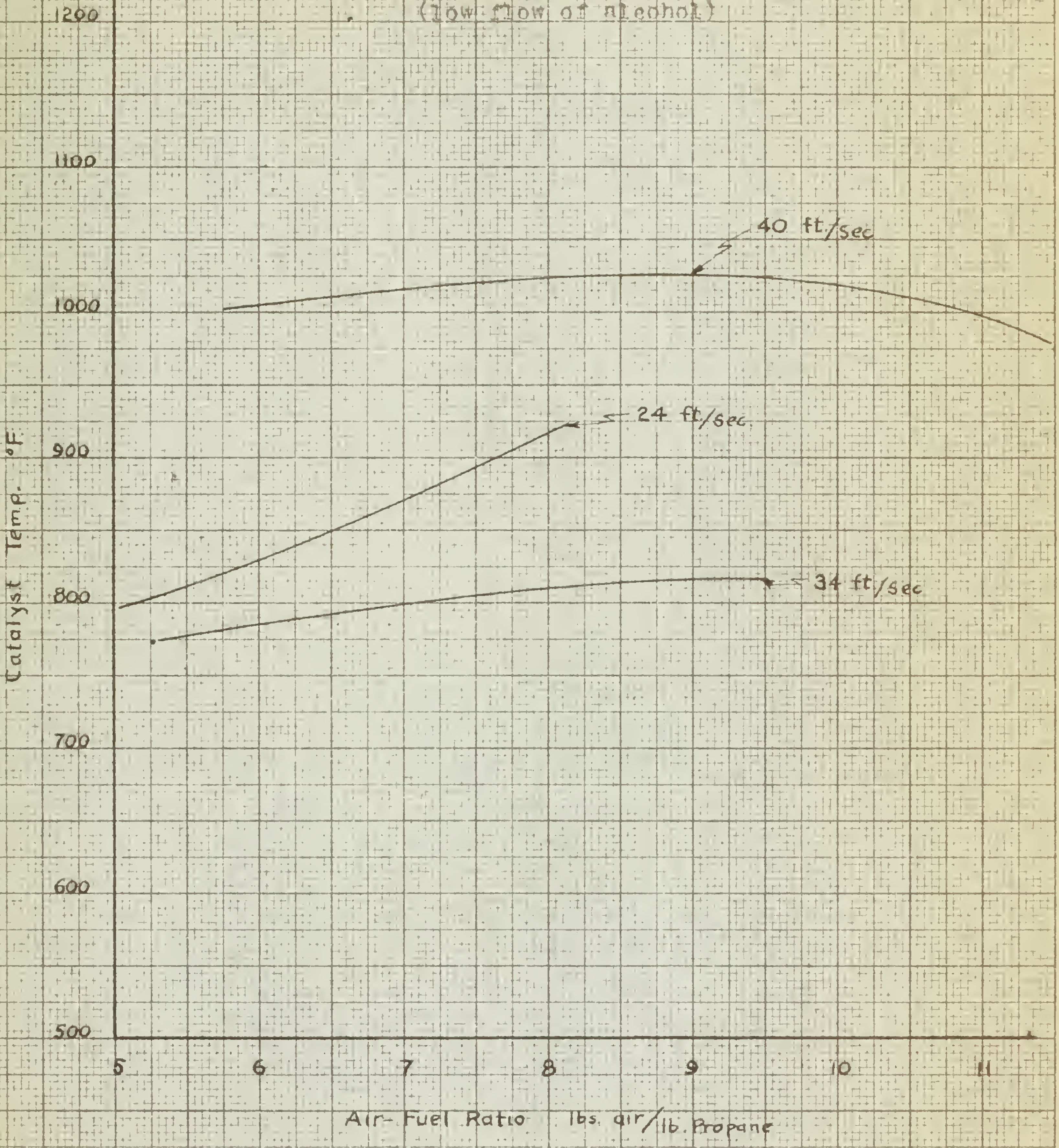
is made and its form.

The tests using a two fuel system were not carried far enough to make any definite deductions from them. The alcohol was merely used as a means of raising the initial temperature so that the propane would react.

Curve 5 does show that the amount of propane oxidized, as measured by the catalyst temperature, is essentially independent of the air fuel ratio for a given velocity in the range of 5 to 12 air fuel ratio. Below 5 the catalyst is poisoned, and above 12 there is insufficient fuel adsorbed. Curve 5 also shows that approach velocity may have a beneficial effect on raising the temperature. The fact that the 40 ft/sec curve gives higher temperatures than the 34 or 24 ft/sec curves was observed repeatedly. It is probably explained by the fact that the formation of the film of reaction products on the surface of the catalyst, was inhibited, which increased the adsorption rate and the quantity of fuel oxidized.

CURVE 5

Test of Propane on Platinum Asbestos with .008" Platinum wire in Asbestos at various upstream velocities (low flow of alcohol)



IV. Summary

In presenting the Conclusions and Summary, it was sought to satisfy the initial object of this paper in presenting indications as to the uses which can be made of catalytic combustion in heat production. The tests provided information on two possible catalyst fuel systems: methanol platinum, and propane platinum. The first system is highly active catalytically, and the second much less so. The tests were run to determine effect of catalyst form, flow rate, and fuel to air ratio on catalytic combustion rates. No design of components for actual use nor analysis of combustion was attempted. The data secured was mostly of a qualitative nature to determine the general relation of the variables, mentioned above, on catalytic combustion.

Conclusions

The use of catalysis as the sole mechanism in combustion, where the maximum heat per unit weight of fuel is desired, is of little value unless the fuel has only one primary stable combustion product. Hydrogen is an example of this, but with the hydrocarbon fuels the products of combustion are varied. As the tests with catalytic combustion show they will not in general be carbon dioxide and water.

The use of catalytic combustion will be as an aid to existing combustion methods. The ignition of a flowing fuel mixture by reaction with a catalyst, which has been demonstrated in this experiment at low flows, may well provide a means of self-ignition in many of the jet combustion units. The disadvantage of having liquids quench the catalysis as found in these experiments may be avoided by using dual fuels. The ability to maintain an igniting temperature in a stream is a function of the adsorption and subsequent reaction rates of the catalyst fuel system, but it is possible to secure these temperatures with very low fuel rates where the fuel is applied to a small portion of the flow area.

The fact that catalytic combustion of hydrocarbons

generally produces some product other than carbon dioxide and water may be used to lower the ignition point of a primary fuel. The primary fuel may not be susceptible to catalytic action but a second fuel of a highly susceptible character will produce combustion products which materially lower the ignition temperature of the primary fuel. Where the flow of gas mixture is through a large area at a relatively low velocity, the catalytic combustion of small quantity of fuel would maintain the walls at an elevated temperature to prevent the quenching action of cold surfaces in the combustion of the main fuel supply.

The use of carriers and promoters with catalysts is advantageous in catalytic combustion since many of the carriers and promoters are refractories which are capable of withstanding high temperatures. Also the use of these agents permits a great reduction in the cost of the catalyst, which is generally high in the pure state.

With any fuel catalyst system, care must be exercised to prepare the catalyst in such a form that it will produce the desired results; but in general the finer the particles the greater the activity per unit weight.

The temperature which a catalyst fuel system can maintain in a stream is determined primarily by the form of the catalyst and not the velocity. The form is important for it

determines the adsorption and reaction rates which in turn determine the heat release. At any fuel air ratio the velocity increase can cause a temperature increase but the relation must be tested for each system before a definite pattern can be established. The form includes the area to volume ratio.

From the information obtained in this work, which is only a preliminary investigation, the use of catalytic combustion offers a possible solution to many of the problems of combustion in a flowing gas. But its use in static combustion holds little promise.

Limitations of the Work and Suggestions For Further Investigation.

The limitations of the experimental work are great since it was only intended as preliminary investigation in the applications of catalytic combustion to fuel combustion problems. The limitation of the descriptive presentation is expected since only a brief review of the high points of such a large subject could be given. In general the experimental setup was rough; but since the objective was general trends, and many tests had to be made, a more complicated and precise setup would have consumed far too much time and would not have given a much clearer insight into the general picture. Perhaps the most severe handicap in

this experiment was the alcohol fuel system which was difficult to control and limited the data on the alcohol system severely.

The suggestions for further work are many since the field has had little work done in it with the objective of developing fuel combustion. The two most promising fields in this writer's opinion lie in the investigation of catalytic ignition at high velocity flows; and the investigation of the effect of using a flame holder of catalytic material with a two component fuel system, one catalytically very active. Another problem as mentioned in the Conclusion is the effect on combustion and stability range of catalytic surface, heated by catalytic combustion, as the material for the combuster in a unit similar to that used in the turbo jet burner. The investigation of the alcohol platinum system with an alcohol control that would permit any range of air fuel ratios would be of considerable value. The development of catalysts and promoters is perhaps the most important phase of all and in this field there are unlimited possibilities.

APPENDIX A

EXPERIMENTAL DATA

Test of methyl alcohol with platinum and promoter catalyst. All flow through the catalyst using test section 1.

A-1a Atmos. press. 30.07 inches Hg. Room temp. 79°F

Time at beginning of test 15:35:30

Time at end of test 15:44:00

Wt. of alcohol used $\frac{15}{16}$ oz.

h(inches water)	M.V. (on screen holder)		M.V.(air)	Temp°F
.175	7.8	345	3	130
.125	12.7	565	3.8	160
.05	15	665	5	210
.02	16	710	8	340
.015 ignition	36	1565	34	1475

A-1b Time at beginning of test 16:25

Time at end of test 17:15:30

Wt. of alcohol used 2-3/8 oz.

h	M.V.		M.V.	
.15	5.1	225	2.2	100
.1	7.2	325	3.6	160
.05	11.4	510	4.2	190
.03	13.2	575	6.0	265
.02	18.5	800	8.8	395
.01 ignition	36	1560	32	1385

A-2a Test of propane and low flow of alcohol on platinum asbestos with .003 inch platinum wire in the asbestos.

Atmos. Press. 30.02 Room Temp. 80°F

Time at beginning of runs 16:41

Time at end of runs 17:12

Wt. of alcohol used 2.3 oz.

Propane tank pressure 110-100 psi gage.

	h	Propane line pressure psi	M.V. (screen)		M.V. (air)	
Run 1	.05	0	22.4	975	10.5	465
		3	21	915	10.1	450
		4	20.5	895	10.0	445
		8	19	830	9.6	425
		12 action ceased	2.0		1.8	
Run 2	.1	0	16	705	7.7	345
		3	18.5	815	9.3	415
		4	18.5	815	9.3	415
		6	18.4	810	9.2	405
		10	18	790	8.9	394
		14 action ceased				
Run 3	.15	0	13	575	6.2	275
		3	22.3	975	10.4	465
		4	23	1005	10.9	485
		6	23.2	1015	11.1	495
		8	23.5	1025	11.4	510
		10	23.4	1020	11.4	510
		14	23.0	1005	11.0	490
		18 action ceased				

APPENDIX B

COMPUTATIONS

1. Air Metering

Refer to L. S. Marks, "Mechanical Engineers Handbook", pages 2098-2099.

Volume rate of flow.

$Q = YMCA\ 2gh$

$Q = ft^3/sec$

Y = expansion factor

M = meter constant

C = coefficient of discharge

A = orifice area in sq.ft.

h = differential head in feet of fluid metered.

Orifice diameter = 1.531 inches

Pipe diameter = 3.00 inches

For conditions in this experiment the value of Y, M, and C taken from Marks are given below.

$Y = 1.00$

$M.C. = .625$

Area of orifice = .0128 sq.ft.

The h as read from data will be in inches of water to convert to feet of air.

h(inches water) 68 = h(feet of air)

Substituting in equation for Q

$$Q = 1.825 \times .0128 \quad 2.32.2 \times h \times 68$$

$$= .53\ h(\text{in inches of water}) \qquad Q' \text{ in cu.ft./sec.}$$

To convert cu. ft. of air to pounds

$$Q\ \left(\frac{\text{cu.ft.}}{\text{sec.}}\right)\ .0765 = W\ \left(\frac{\text{pounds}}{\text{sec}}\right)$$

To convert pounds of propane to cu. ft.

$$\frac{W\ (\text{pounds})}{.1195} = Q(\text{cu.ft.})$$

Temperatures are converted from M.V. to degrees Fahrenheit by tables of chromel-alumel thermocouples.

Average stream velocity upstream of catalyst surface,

$$v = \frac{Q\ (ft^3)}{A\ (ft^2)} = \frac{ft}{sec}$$

diameter test section 1 = 1 inch Area = .00545 sq.ft.

$$v = \frac{Q}{.00545}\ (\text{air + fuel})$$

$$\text{Alcohol fuel rate} = \frac{\text{Wt. used (pounds)}}{\text{time(secs)}}$$

TABULATED COMPUTATIONS

A-1a Test of methyl alcohol on platinum and promoter catalyst. Object: to obtain a relation of catalyst temperature and upstream velocity with constant fuel rate.

	h inches water	Q air cu.ft/sec	W air lbs/sec	V ft/sec	Temp. screen °F	Temp. air °F
	.175	.222	.0169	40.5	345	130
	.125	.188	.0144	34.5	565	160
	.05	.118	.00906	21.7	665	210
	.02	.075	.00575	13.8	710	340
ignition	.015	.065	.00496	11.9	1565	1475

Alcohol fuel rate = .000115 pounds/sec

A-1b

	.15	.205	.0157	37.6	225	100
	.1	.168	.0128	30.8	325	160
	.05	.118	.00906	21.7	510	190
	.03	.092	.00705	16.9	575	265
	.02	.075	.00575	13.8	600	395
ignition	.01	.053	.00414	9.9	1560	1385

Alcohol fuel rate = .0000475 pounds/sec

A-2a Test of propane and low flow of alcohol on platinum asbestos with .005 inch platinum wire in the asbestos.

Object: To obtain relation of catalyst temperature and fuel air ratio for various velocities.

Run 1

Air h(inches water)	Q(ft^3/sec)	W air
.05	.118	.0144

Propane lb/in^2	W fuel lb/sec	Q fuel cu.ft./sec	V ft./sec	$\frac{\text{W air}}{\text{W propane}}$	Temp °F Screen	Temp °F Air
0	0	0	21.7		975	470
3	.0018	.0152	24.0	8	915	450
4	.0019	.0161	24.3	7.6	895	445
8	.0024	.0203	24.8	6.0	830	430
12	.0029	.0245	25.6	5.0	no re-action	

Run 2

Air h	Q	W
.1	.168	.0128

0	0	0	30.8		705	345
3	.0016	.0152	33.6	9.35	815	415
4	.0019	.0161	33.3	8.85	815	415
6	.0021	.0176	34.0	8.0	810	410
10	.0027	.0226	36.7	6.24	790	395
14	.0032	.0268	37.4	5.25	no re-action	

Run 3

Air	h(inches water)	Q(cu.ft./sec)	W(lb./sec)
	.15	.205	.0157

P propane p.s.i.	W fuel lb/sec	Q cu.ft./sec	V ft./sec	$\frac{W_{air}}{W_{fuel}}$	Temp °F Screen	Temp °F Air
0	0	0	37.6		575	275
3	.0018	.0162	40.5	11.4	975	465
4	.0019	.0161	40.6	10.8	1005	485
6	.0021	.0176	40.7	9.8	1015	495
8	.0024	.0203	41.3	8.55	1025	510
10	.0027	.0226	41.5	7.55	1020	510
14	.0032	.0268	42.3	6.33	1005	490
18	.0038	.0308	42.9	5.40	no reaction	

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